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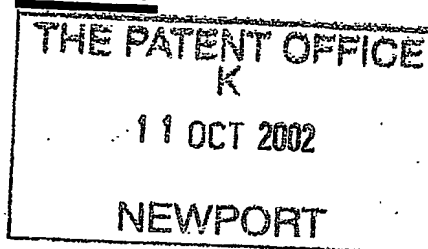
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AOTI OPERATING COMPANY, INC.
131 NW HAWTHORNE AVENUE
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BEND, OREGON 97701, US

Patents ADP number (if you know it)

813805002

If the applicant is a corporate body, give the country/state of its incorporation

DELAWARE, USA

4. Title of the invention

SEMICONDUCTOR MONITORING INSTRUMENT

5. Name of your agent (if you have one)

NOVAGRAAF PATENTS LIMITED

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THE CRESCENT
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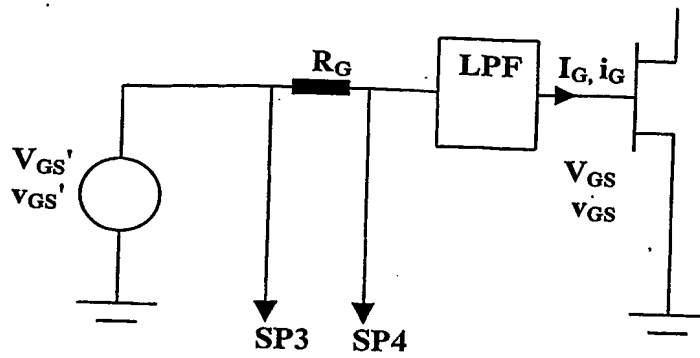


Figure 4

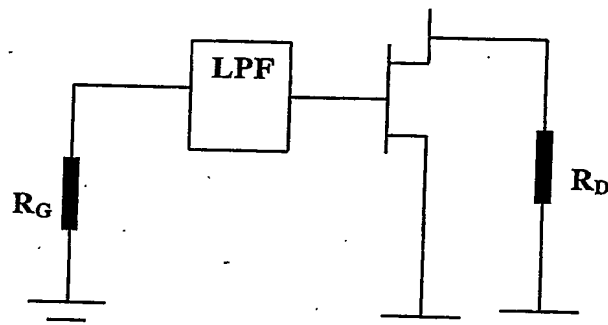
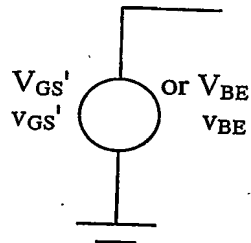


Figure 5

Input generator



Output generator

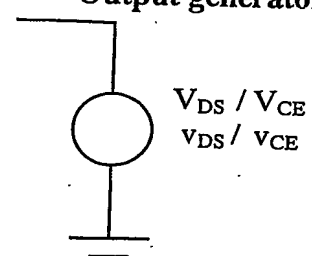


Figure 6

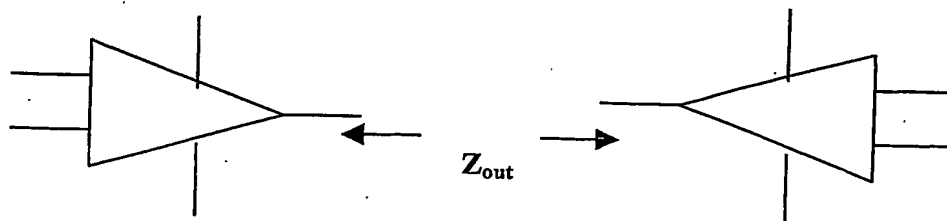


Figure 7

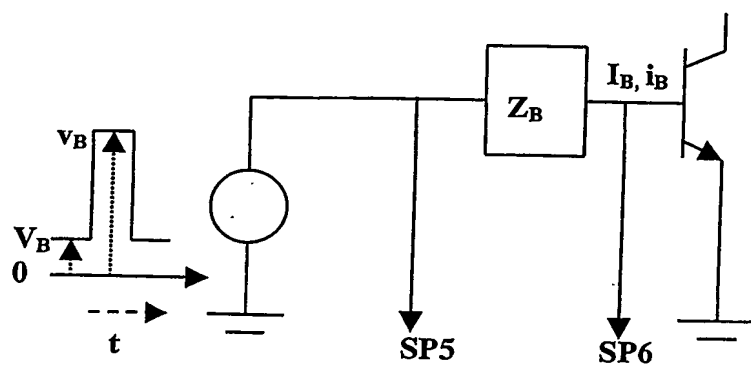


Figure 8

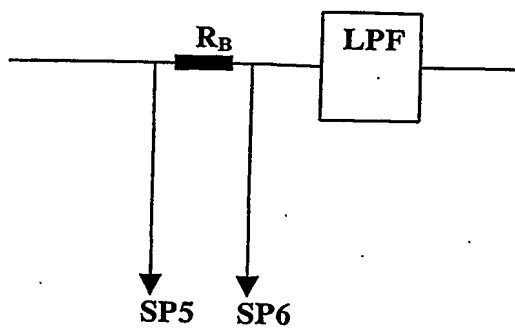


Figure 9

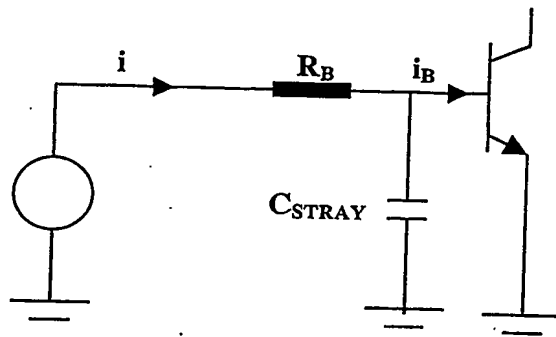


Figure 10

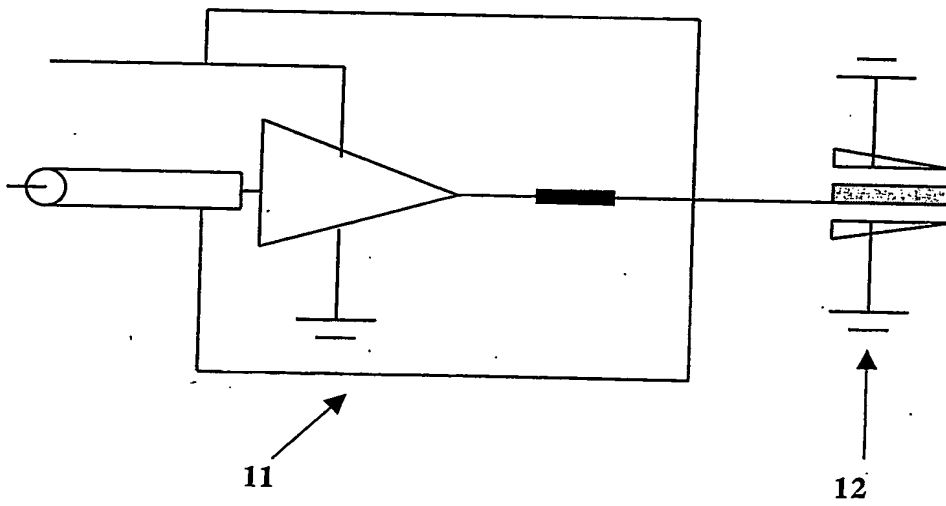


Figure 11

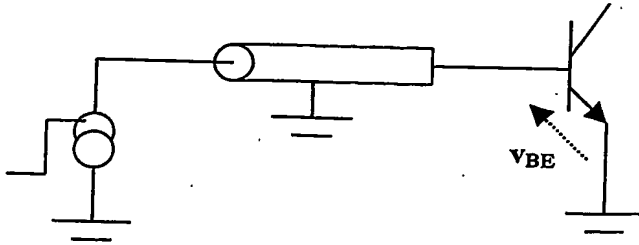


Figure 12

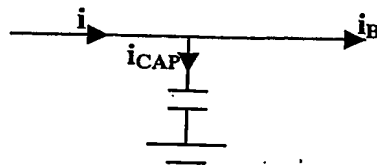


Figure 13

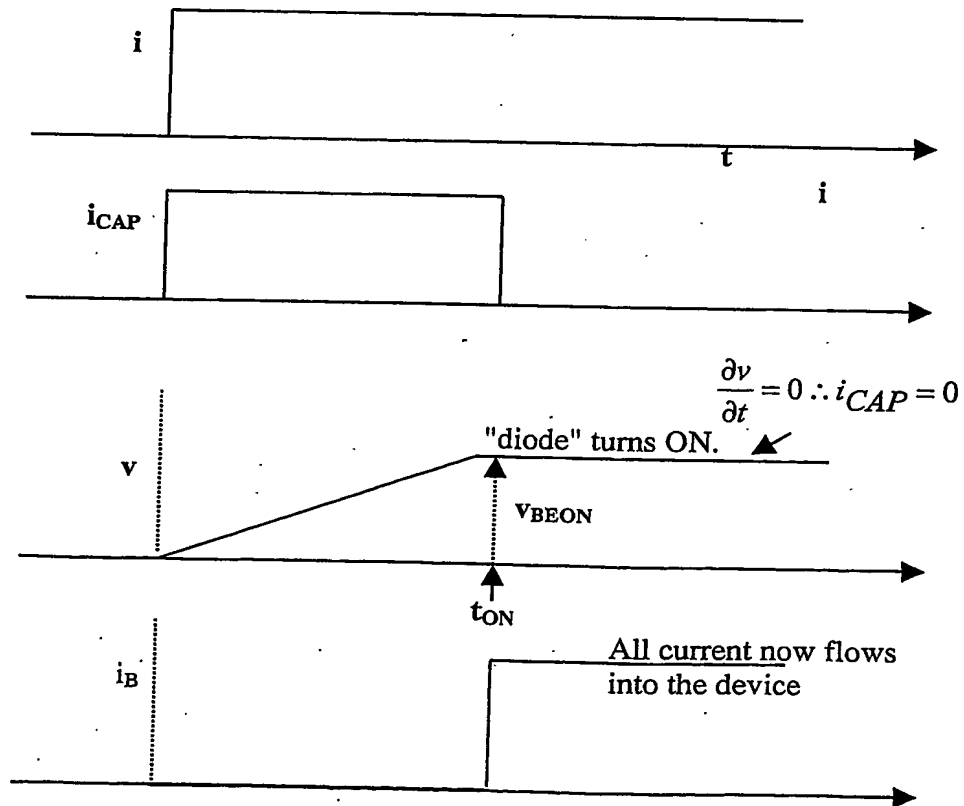


Figure 14

SEMICONDUCTOR MONITORING INSTRUMENT

5 The present invention relates to a semiconductor monitoring instrument, and in particular to an instrument for measuring the dynamic current-voltage conduction characteristics of a semiconductor device under test, especially at RF frequencies. The invention also relates to a method of such measurement.

10 For semiconductor devices of all types, including transistor devices, semiconductor LEDs and lasers and other semiconductor devices, there is a general requirement to be able to measure the conduction current-voltage (I-V) characteristics of a device to obtain a realistically representative picture of its I-V performance under operational conditions.

15 This applies to most types of transistor devices (discrete or integrated) including without limitation:

- bipolar transistors: NPN and PNP devices.[1]
- silicon FETs including MOSFETs (metal-oxide-semiconductor field-effect transistors) and LDMOS (laterally diffused metal oxide semiconductor).[1]
- 20 • MESFETs (metal-electrode-semiconductor field-effect transistors. Most commonly GaAsFETs when fabricated in GaAs).[2]
- HEMTs (high electron mobility transistors).[2]
- HBTs (heterojunction bipolar transistors).[1,2]

25

Note that devices marked [1] are generally fabricated in silicon (Si), silicon-germanium (SiGe) or silicon carbide (SiC), whereas devices marked [2] are generally fabricated using high-electron mobility compound semiconductor materials such as gallium arsenide (GaAs) or indium phosphide (InP).

30

Increasingly, modern electronic systems rely upon semiconductor devices operated under large-signal conditions. For example, mobile phone handsets, power amplifiers, base stations, radars, missile guidance systems/electronic instruments, and other like electronic systems use semiconductor integrated circuits (ICs) or discrete devices which are designed to operate under such large signal conditions, that is to operate over a large part of the available output I-V range. It becomes particularly important therefore that the I-V characteristics of the device are accurately characterised.

Traditionally, I-V characteristics of a semiconductor device have been measured either at dc, or under very slowly varying conditions. These are then extrapolated to give an indication of I-V characteristics at higher operating frequencies. Increasingly, the approximation involved in this extrapolation is presenting a problem at higher (e.g. microwave or RF, i.e. GHz) frequencies, particularly in devices operating under large-signal conditions.

Almost all semiconductor devices exhibit significant differences between behaviour at higher, RF frequencies and behaviour under direct current (dc) or low frequency conditions. The difference in operational performance of devices can produce a large difference in operational performance of circuits and therefore of systems. In consequence, a circuit design based on dc measurements and built and operated at RF or microwave frequencies will not perform as designed. As circuits have become more sophisticated, and in particular have tended to operate under larger signal conditions, the difference has become more significant.

Prior art systems are of IV measurement, which rely upon extrapolation from dc or low frequency test conditions, are therefore no longer satisfactory.

It is an object of the present invention to mitigate some or all of the above disadvantages.

5 It is a particular object of the present invention to provide a measuring instrument and method for accurate measurement of the conduction I-V characteristics of a device under test at high (RF or microwave) operating frequencies to obtain a more realistic indication of I-V characteristics under real operating conditions.

10 It is a particular object of the present invention to provide, for transistor devices of all types and also semiconductor LEDs and lasers and other semiconductor devices, an instrument which can accurately measure the current-voltage conduction (I-V) characteristics of the device under test at a high-enough rate to inhibit dispersive processes from operating, yet at a low-
15 enough rate to ensure that the measurements are free from reactive current flow components. The results of such measurements are referred to herein as the "dynamic I-V conduction characteristics of the device under test". A secondary objective is to measure the dc or "static" slow-sweep I-V characteristics as commonly made by many other instruments.

20

In accordance with the invention at its broadest an instrument for measuring dynamic I-V conduction characteristics of a semiconductor device under test comprises a means to apply an adjustable bias at both the input and the output of a device under test comprising fast, superimposed rectangular bipolar
25 pulses and a means to measure the current response thereto at both input and output.

As indicated, within this industry there is a great desirability to be able to determine a properly representative measure of the RF or microwave
30 behaviour of the device from "simple" dc measurements - including pulsed dc

measurements. More precisely, this requires the retrieval of charge or capacitance functions from conduction measurements to produce an RF-valid FET (or HEMT, or bipolar) model from the pulsed measurements.

- 5 The invention achieves this in admirably simple manner in that a user can extract, recover or re-construct the large-signal capacitance (or charge) functions from conductance measurements produced by the device.

10 In principle, I-V curves at RF or microwave frequencies could be measured using any wave form that had a fast enough rate. The problem is one of interpretation. To recover the desired characteristic I-V curves it is necessary to apply a measurement technique which gives the characteristics of the device itself, uncorrupted by and completely independent of the method or instrument used to make the measurement. In other words, we need to apply a wave form
15 which does not corrupt the response. Accordingly, the invention uses step pulses with flat tops.

Preferably, the wave form applied by the instrument is essentially critically damped so as to achieve a minimum rise time up to the point where the pulses
20 become substantially flat. There is a further general requirement that the pulses to be applied must provide a high degree of isolation of the instrument from external influences that would otherwise degrade the performance.

Preferably, the measuring instrument further comprises means to measure dc
25 I-V conduction characteristics of a semiconductor device under test by applying a dc signal at both the input and the output of the device under test.

In this preferred embodiment the instrument is therefore capable first of measuring the dc I-V characteristics, and also, by allowing a single bias point
30 to be set and then, starting from there, allowing all operating or instantaneous

I-V points to be accessed or measured by application of the bipolar pulse bias, to obtain a representative indication of the dynamic I-V conduction characteristics. In accordance with the invention stepped pulses are applied to both input and output and the current at each point is measured quickly. The invention therefore requires two pulses each of which can be of either positive or negative sense and separately variable, that is two synchronised bipolar pulses.

The particular problem encountered at RF and microwave frequencies is that of applying a suitable biasing pulse, maintaining the pulse shape and integrity, and rapidly measuring current responses, whilst at the same time achieving device stability. At these frequencies, practical devices tend to undergo spurious oscillation when under test, which the skilled person will appreciate is one of the primary reasons why testing has conventionally been carried out at low frequency or dc.

It has been suggested in the prior art that higher frequency pulses could be applied while keeping devices stable by use of a "bias tee". However, the capacitances within such as bias tee give the bias tee itself its own frequency response, which in practice limits the speed of the pulse which can be used. By contrast, in the present invention, fast step, generally flat topped pulses can be achieved at high pulse rates, and in particular with pulse rates below about one μ s, can be achieved.

In a particular embodiment of the invention, this is achieved in that the means to apply the adjustable bias at the input and output comprises a high stability voltage source serially connected to the input/output via a resistor, and preferably further serially connected especially at the input side through a low pass filter.

The power supplies are selected to have very low output impedances even at the high frequencies under test.

- The effect of this arrangement as incipient spurious oscillations arise will be understood. To spurious oscillation disturbances the near perfect power supplies appear to be shorts. The circuit therefore functions in effect as a resistive termination, and it is well understood that such a resistive termination is effective as a means of unconditionally stabilising a transistor or like device.
- 10 The resistor used to achieve this resistive termination must be very low in parasitic reactances. For a FET type device stabilisation on the output side is preferably achieved by a resistance in the range of a few Ω to some 10s of Ω , for example 5 Ω to 100 Ω . The resistance on the input side is preferably an order of magnitude greater, for example being some 10s of Ω to 100s of Ω , for
- 15 example 50 Ω to 500 Ω . For a bipolar type device resistances are likely to be an order of magnitude greater, for example 500 Ω to 5k Ω on the input side.

- The inclusion of an optional low pass filter represents a second stabilisation measure which increases the effectiveness of stabilisation of the device under test at input and output. The low pass filter is selected such as to be effectively transparent at the pulse rates and rise times under test, but act to inhibit time dependent variations in current or voltage at higher oscillation frequencies.
- 20
- 25 Conveniently, the low pass filter comprises a shunt capacitor across the resistance followed by a series inductor.

Sample measuring points are provided across the resistor. In particular, current and/or voltage measuring means are provided to measure input and

response currents and voltages at high speed, preferably within 5 ns, and in particular within 1-2 ns. Input and output pulse generators are preferably in the form of operational amplifiers having output impedances kept low preferably no more than a few Ω , for example less than 5 Ω , and in particular
5 below 1 Ω , even at RF and microwave frequencies. This enables short pulses to be generated, preferably below 100 ns, and for example down to a few tens of ns.

In accordance with a further aspect of the invention, a method for measuring
10 dynamic I-V conduction characteristics of a semiconductor device under test comprises applying an adjustable bias at both the input and output of the device under test comprising fast, super imposed rectangular bipolar pulses, and rapidly measuring the current response thereto at both the input and output. The method in particular comprises use of the instrument as above
15 described.

Preferred features of the method and preferred or necessary parameters for the bipolar pulse, pulse rates, measurement times etc will be understood by analogy with the foregoing description of the preferred embodiments of the
20 instrument.

The invention will now be described by way of example only with reference to Figures 1 to 13 of the accompanying drawings wherein:

25 Figure 1 is an illustration of a comparison of typical dc and high frequency characteristics for a typical device to be tested;

Figure 2 illustrates the principle of resistively terminating a FET;

Figure 3 illustrates an arrangement for an embodiment of the invention supplying power at a source of an FET;

Figure 4 illustrates an arrangement for an embodiment of the invention supplying power at a gate of an FET;

Figure 5 illustrates an effective equivalent circuit to Figure 4 as far as spurious noise oscillations are concerned;

5 Figures 6 and 7 illustrate preferred input and output pulse generators;

Figures 8 and 9 illustrates an example circuit in accordance with the invention for measuring the input side of a bipolar transistor;

Figure 10 illustrates the problem of stray shunt capacitance;

10 Figure 11 illustrates schematically an the example measuring head for use with a device under test;

Figures 12-14 illustrate an embodiment of the invention adapted to produce particularly short pulse lengths of the order of 1 ns.

15 Important characteristics of the basic instrument and method will be understood by discussion of figures 1 to 7.

These figures relate to an example instrument in accordance with the invention which embodies a scheme for enabling simultaneously bias + pulses + device stability.

20

Typical output characteristics for a semiconductor device under test are shown in figure 1. In this figure solid curves are dc ("static") characteristics, broken curves are dynamic i_D (i_C) - v_{DS} (v_{CE}) characteristics, o is the bias point, I_D (I_C) and V_{DS} (V_{CE}) are respectively the dc currents and voltages, and i_D (i_C) and v_{DS} (v_{CE}) are respectively the dynamic currents and voltages.

25

The different notations illustrate the application of the measuring device to different test devices, and refer to either FET or bipolar types of transistors. For an FET or like device reference is made to drain (D) and source (S)

whereas for a bipolar or like device reference is made to collector (C) and emitter (E). The principles of operations are generally the same.

5 A measuring device in accordance with the invention applies the dc bias V_0 and also provides synchronous ("bipolar") pulses around this bias point to the device-under-test.

10 However, parasitic impedances arise in series with the source or (base) and with the drain or (collector). Also there are parasitic impedances from these terminals to ground. These impedances arise inevitably from the device under test itself, from jigs supporting the device under test, from the measuring instrument, connecting cable, etc.). The existence of these parasitic impedances means that the device under test is subject to a risk of oscillation.

15 This is the primary problem which has rendered attempts in the prior art to use higher frequency pulse-based measurement devices impractical. Meaningful measurements cannot proceed with an oscillating device. The question therefore arises as to how to achieve device stability. With the device in accordance with the invention arrangements are made to precisely ensure
20 stability. How this is achieved is discussed below.

In order to unconditionally stabilise a transistor microwave engineers tend naturally to resistively terminate the output of the device - drain to ground for an FET and collector to ground for a bipolar. This principle is illustrated in
25 figure 2. Although an FET transistor is shown it will be understood that the same approach is also applicable by analogy to a bipolar type device.

It is a key feature of the present invention that the device is adapted to mimic this principle, preferably at both input and output.

Figure 3 illustrates how this is achieved in the example device on the output side.

R_D must be low in value, typically from a few ohms to some tens of ohms. The resistor must also be very low in parasitic reactances.

SP1 and SP2 are sampling points. From measurements at these points, using A - D sampling, the voltages V_{DS} and v_{DS} are obtained. Then, because these voltages are measured across the almost pure resistor, their difference leads to the currents I_D and i_D - and this i_D is the required conduction current.

Hence R_D performs two functions simultaneously:

- (i) the stabilisation measure, and;
- (ii) the means of current measurements - both dc (I_D) and conduction (i_D).

Figure 4 illustrates how this is achieved in the example device on the input side (gate or base).

The device is arranged electronically in similar manner to that described on the input side. The example device now measures the voltages at the sampling points SP3 and SP4, hence the potential difference across the resistor R_G , which yields the conduction currents I_G and i_G (or I_B and i_B for a bipolar). Again the choice of R_G is critical, being some tens to hundreds of ohms and very low in parasitic reactances.

A very important feature is that the introduction of the low-pass filter (LPF) represents a second stabilisation measure.

As far as spurious "incipient" oscillation or noise signals are concerned the circuit appears as shown in Figure 5.

5 The low-pass filter (LPF) has to be transparent at the pulse rates and rise times attendant to the measurement, but also must be such as to quench and inhibit time-dependent variations in current or voltage at higher (oscillation) frequencies.

10 In practice the LPF is realised simply as a shunt capacitor across R_G followed by a series inductor in the gate (or base) lead.

This arrangement:

- Keeps the device under test stable.
- Allows input and output conduction currents to be measured under dc and
15 dynamic conditions.
- Allows dc biases and pulses to be applied simultaneously to the device under test.
- Allows fast (few tens of nanoseconds rise time) pulses to be applied.
- Provides a measure of buffering or isolation of the device under test, which
20 preserves the pulse shape and integrity.
- Provides a measure of protection from device destruction by current runaway - especially with bipolar devices.
- Provides a measure of short-circuit protection for the measuring
25 instrument.

There are also important special aspects regarding the pulse generators, at both the input and the output sides. These are indicated in Figure 6. These generators are realised in practice in the forms of operational amplifiers (op

amps), as shown in Figure 7, which illustrates both an input op amp (left) and an output op amp (right).

The important requirement is that for each op amp the output impedance Z_{out} must be kept extremely low - even at RF and microwave frequencies. For this the op amps need to be specially selected.

The consequence is that this scheme allows short pulses to be generated - down to a few tens of nanoseconds (ns).

10

Bipolar Transistor Measurements present particular difficulties. Figures 8 and 9 illustrate the principles of an embodiment of the invention in measuring, at constant base current I_B , the dynamic I-V characteristics of bipolar transistors - which are notoriously unstable.

15

There are two important issues;

- (i) How to measure the dynamic I-V conduction characteristics with I_B constant as parameter, whilst keeping the device stable.
- (ii) Defining the measurement conditions for valid measurement of the dynamic I-V conduction characteristics uncorrupted by the reactive effects.

20

Considering issue (ii) first of all. The measurement conditions are satisfied by maintaining the pulse length greater than a time as defined by the following inequality:

25

$$t_{pulse} \geq t_{ON} = \frac{(\beta + 1)i_{BSTEP}}{2\pi f_T \left(\frac{kT}{q} \right)} R_B \ln \left[1 + \frac{v_{BEON}}{i_{BSTEP} R_B} \right]$$

In which: t_{ON} is the time required to fully turn the transistor on, β is the dc collector-to-base current ratio, f_T is the current transition frequency and all the remaining quantities are readily known. At normal ambient temperature ("room" temperature) $T = 298K$ and the kT/q ratio is 0.025V.

5

There is one connection approach that might ideally be desired - but which cannot be achieved - which is to drive the base input from a constant current source. Microwave and RF engineers, will understand that this cannot practicably be achieved. At the high frequencies associated with the very short
10 pulses only S-parameters may be used and these demand matched terminations - not the open or short-circuit approximations used with h-parameters or y-parameters, etc.

(Under small-signal linearized conditions one can measure S-parameters and
15 then transform the results into h, y, z ABCD or other sets of parameters. However, under large-signal conditions this cannot be done.)

So, for measuring a bipolar transistor, what has to be established is the type of circuit indicated in Figure 8. As before, sampling points SP5 and SP6 are
20 immediately followed by A > D converters within the measuring instrument.

Regarding Z_B , this required series impedance is:

- (a) realistic in the practical case, and
- 25 (b) needed for device under test stability.

With Z_B it is now possible to measure directly what is required, as follows:

Z_B is realised as resistor R_B in series with a low-pass filter (LPF), indicated in
30 Figure 9.

R_B is typically a few hundreds of ohms in value and it must also be very low in parasitic reactances. Note that the value range is around an order-of-magnitude larger than for R_D described in conjunction with measurements on
 5 FETs, see above. The LPF has to be "transparent" at the pulse rates and rise times in use. In this method fast-sampling is used at the SP5 and SP6 points (i.e. A-D5 and A-D6) and iterate V_B , v_B (digitally) until I_B , i_B are as set - or as desired.

10 Figure 10 illustrates an embodiment of the device specifically adapted for measurement at very low i_B values - in the region of $1\mu A$ order of magnitude.

The stray instrument capacitance C_{STRAY} represents a problem and special low-capacitance buffering techniques, internal to the measuring instrument,
 15 are required to keep the effective stray capacitance low - down to the order of a few pF. As this stray capacitance is made smaller, so i_B can be set ever smaller - within known accuracy limits.

For contacting to the device-under-test outside the instrument there are two
 20 possibilities:

- (i) for packaged devices: a cabled connector and the device jig, and:
- (ii) for bare chips: a cable run followed by an RF on-wafer prober.

These RF probers are precision units and lower frequency "standard" probers
 25 are completely useless in this RF or microwave context.

There is, however, a problem with the total series inductance and the total shunt capacitance of the cable connecting to the wafer prober. In general terms, $50\ \Omega$ cables are not readily available but occasionally $10\ \Omega$ cables may

be used. Care must be taken regarding the selection of the minimum pulse period and often 100 ns cannot be used.

In order to minimise this problem a remote head (11) is installed on the same micromanipulator as the RF on-wafer prober (12). The arrangement is shown in circuit-schematic form in Figure 11.

Figure 12 illustrates an embodiment of the device specifically adapted for pulse lengths having an order of magnitude of 1 nanosecond (1 ns).

10

A problem arises at such short pulse lengths if a connection is made using a cable run that is predominantly capacitive, as shown in Figure 12. This is approximately equivalent to the simple circuit shown in Figure 13 which shows the current i_{CAP} that flows in the capacitive element of the cable.

15

The key aspects are:

- (I) Start from $v_{BE} = 0$ (i.e. $i_B = 0$), then:
- (II) Turn the pulse on - from a current generator source.

20

The waveforms of Figure 14 show the effects - remembering that $i = C \frac{dv}{dt}$

The time t_{ON} can be ascertained by continually sampling (since when $i_B = 0$, $i_C = 0$). The sample acquisition time is around 1 to 2 ns. Therefore it is possible to sample i_C and this enables measurements at pulse lengths of the order of 1 ns.

25

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